



# UK Patent Application (12) GB 2 322 941 (13) A

(43) Date of A Publication 09.03.1998

(21) Application No 9804828.3

(22) Date of Filing 09.03.1998

(30) Priority Data

(31) 9704737

(32) 07.03.1997

(33) GB

(51) INT CL<sup>6</sup>

A61B 5/00, G01N 21/37

(52) UK CL (Edition P)

G1G GPB G6A

U1S S1032 S1296 S1517

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31(3), pp. 284-290, May 1993 Physics in medicine and  
biology, Vol. 38(12), pp. 1911-1922, Dec 1993

(58) Field of Search

UK CL (Edition P) G1G GPB  
INT CL<sup>6</sup> A61B 5/00 5/14, G01N 21/17 33/483 33/487  
33/49  
ONLINE: WPI INSPEC

(54) Abstract Title

In-vivo photoacoustic measurement

(57) A biological parameter is measured by directing laser pulses from a light guide (10) into a body part consisting of soft tissue, such as the tip of a finger (12), to produce a photo-acoustic interaction. Sound waves (14) generated by absorption of the optical beam are detected by a transducer (16). The detector and optical beam guide are housed in a body-part shaped sensor head device (figures 2 to 16), and are preferably not co-linear with one another. Analysis of the transducer output enables calculation of the desired parameter, e.g. blood glucose concentration.

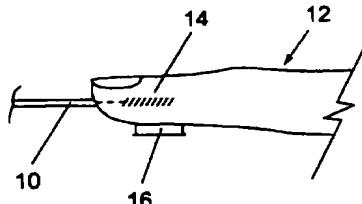


Fig. 1a

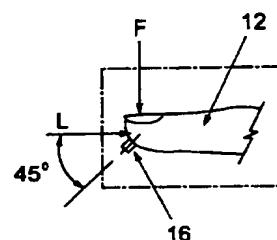


Fig. 1b

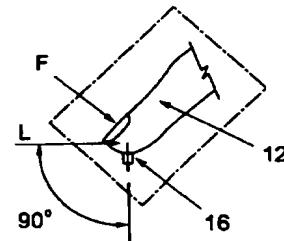


Fig. 1c

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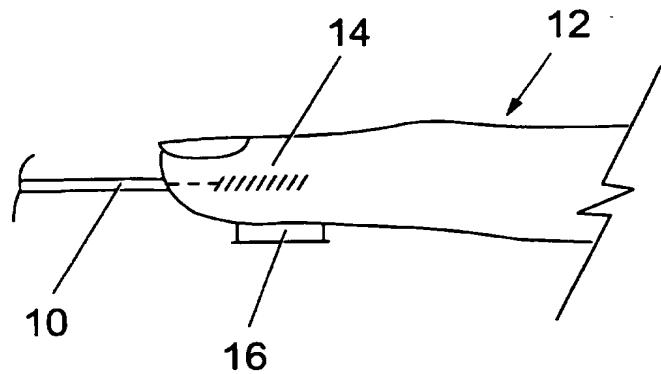


Fig. 1a

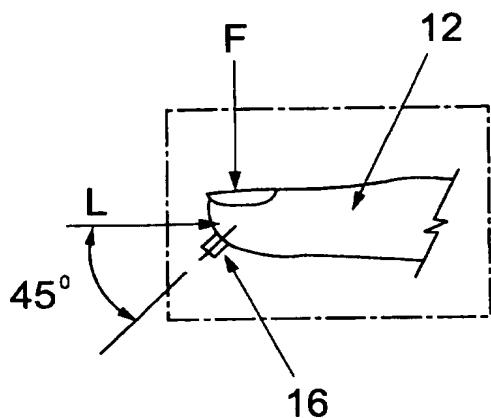


Fig. 1b

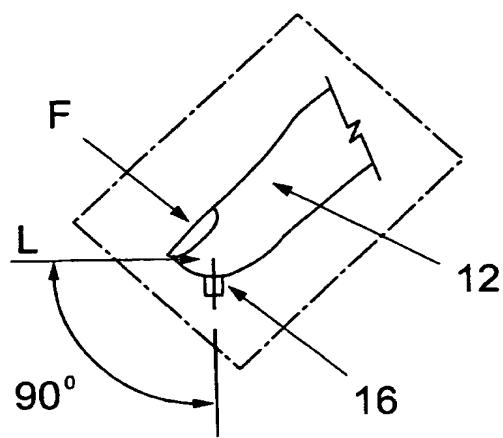
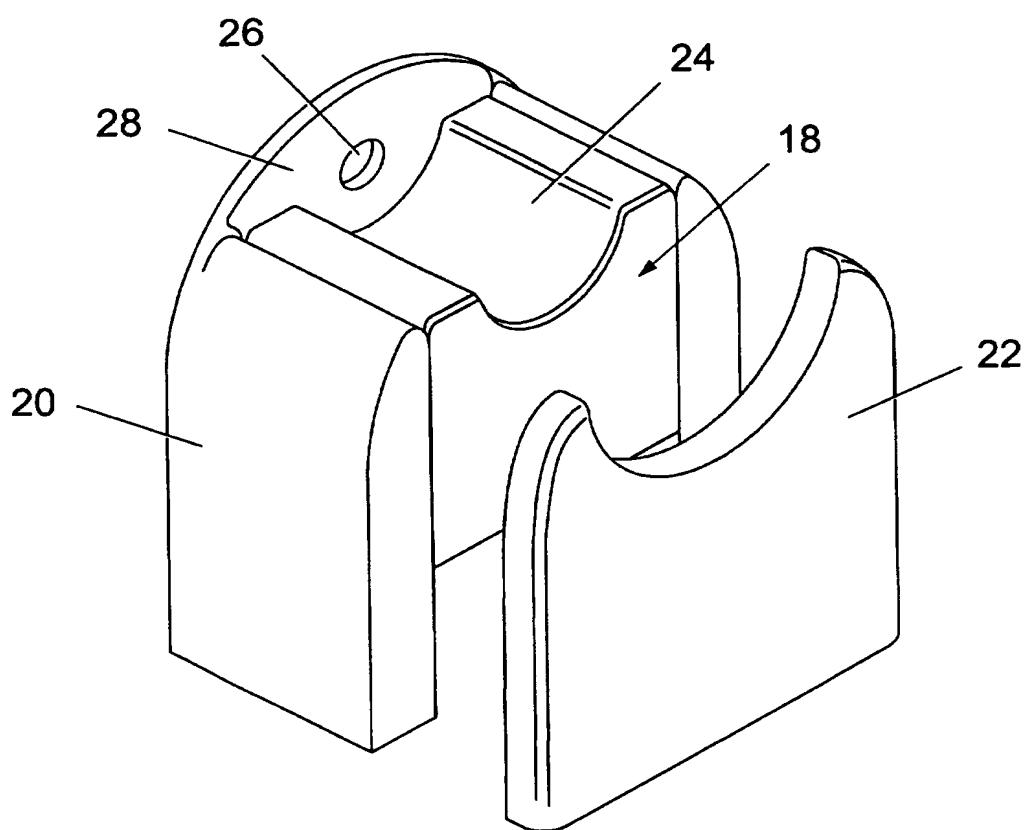


Fig. 1c



*Fig. 2*

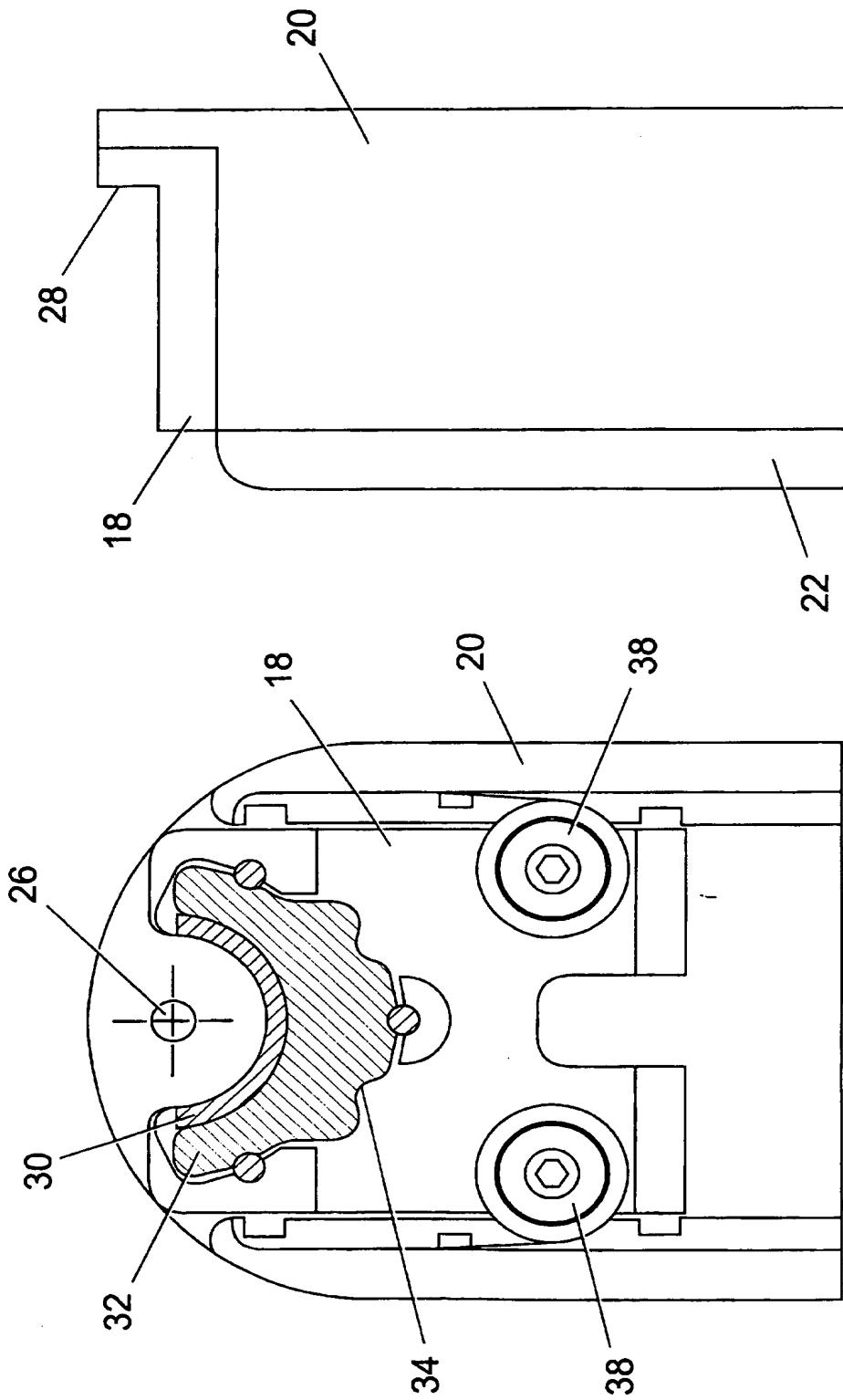
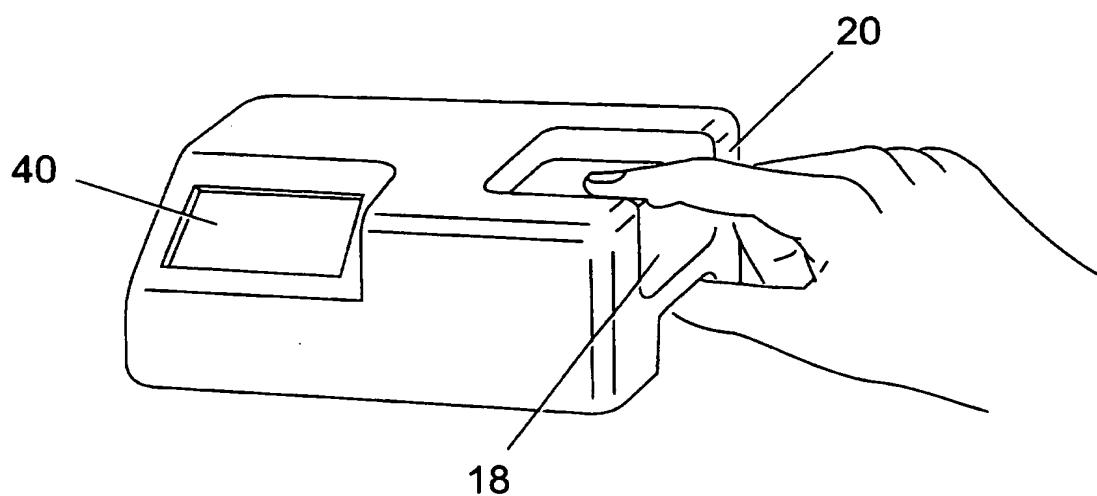


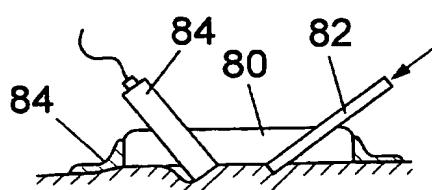
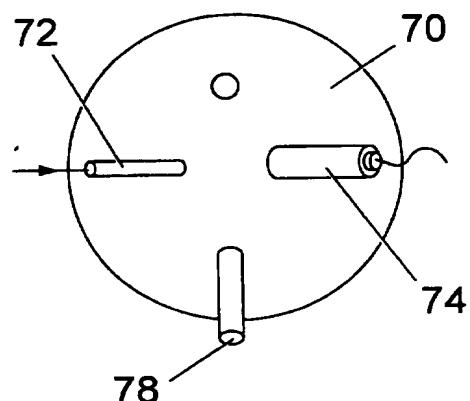
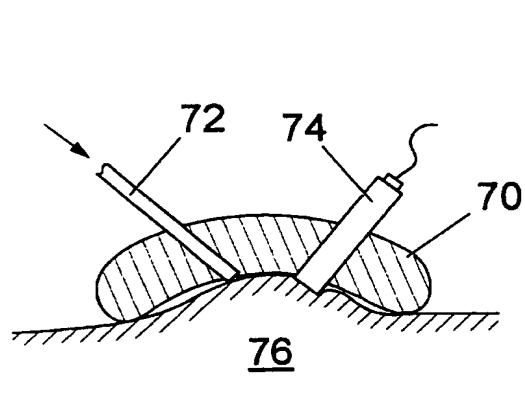
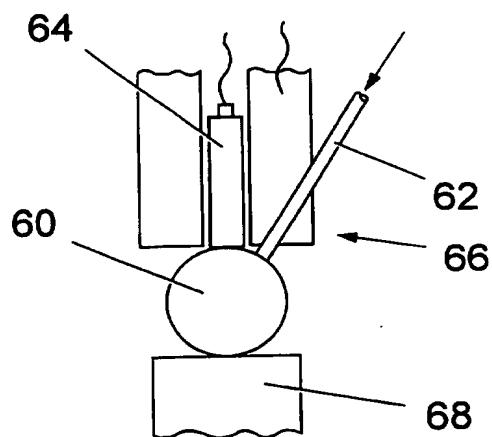
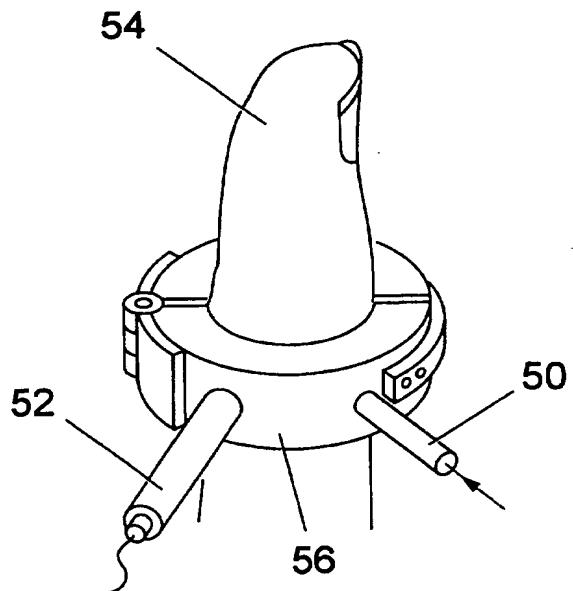
Fig. 3

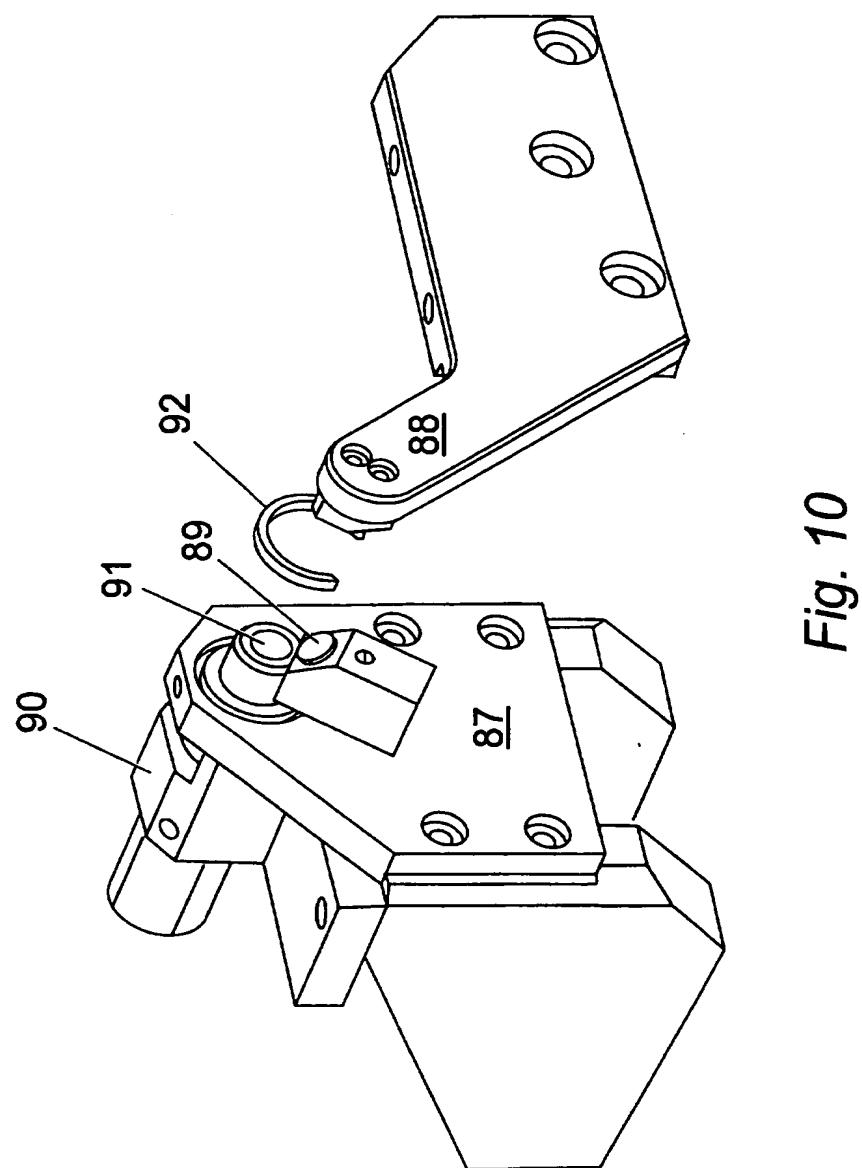
Fig. 4

4 / 16



*Fig. 5*





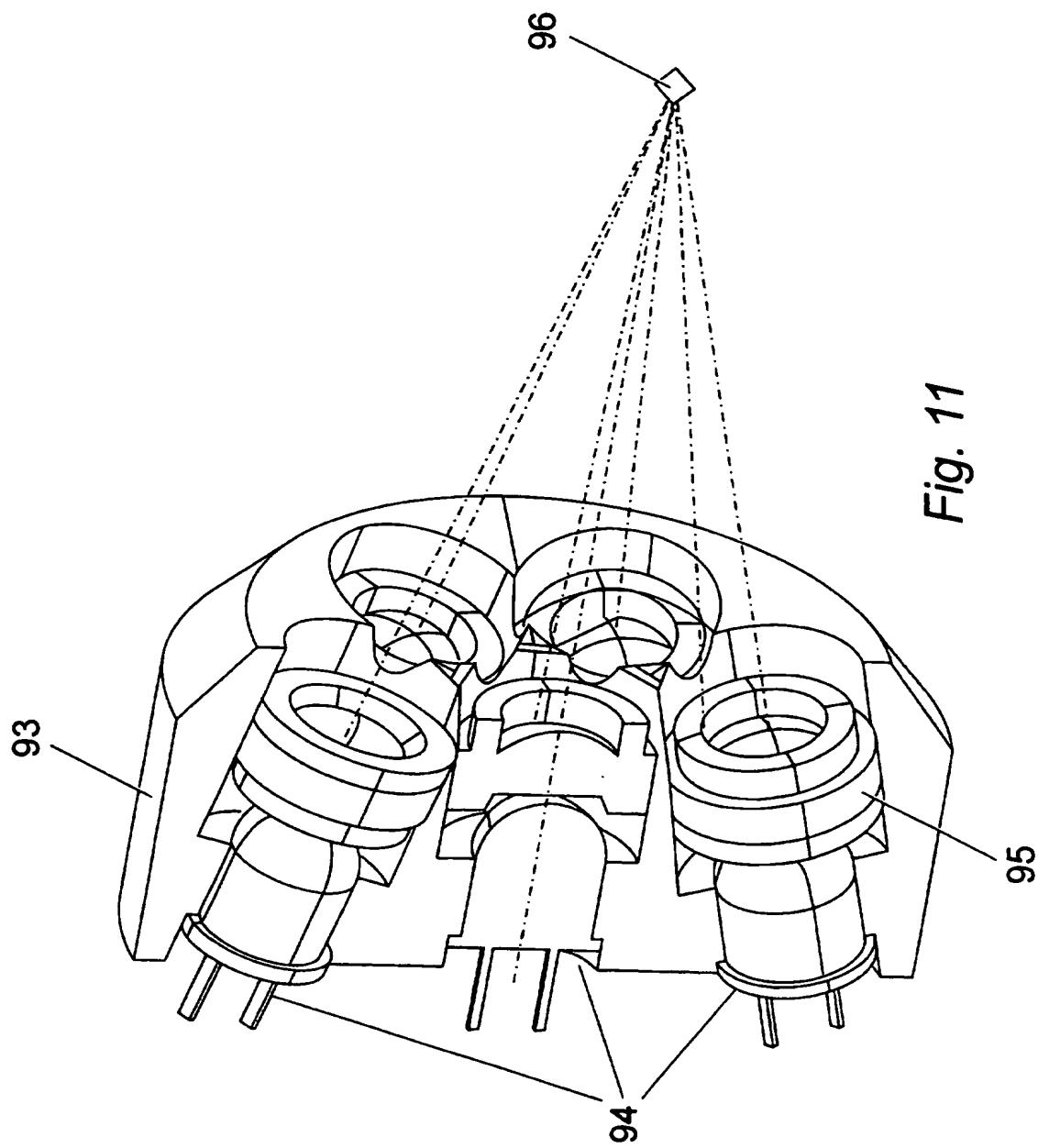


Fig. 11

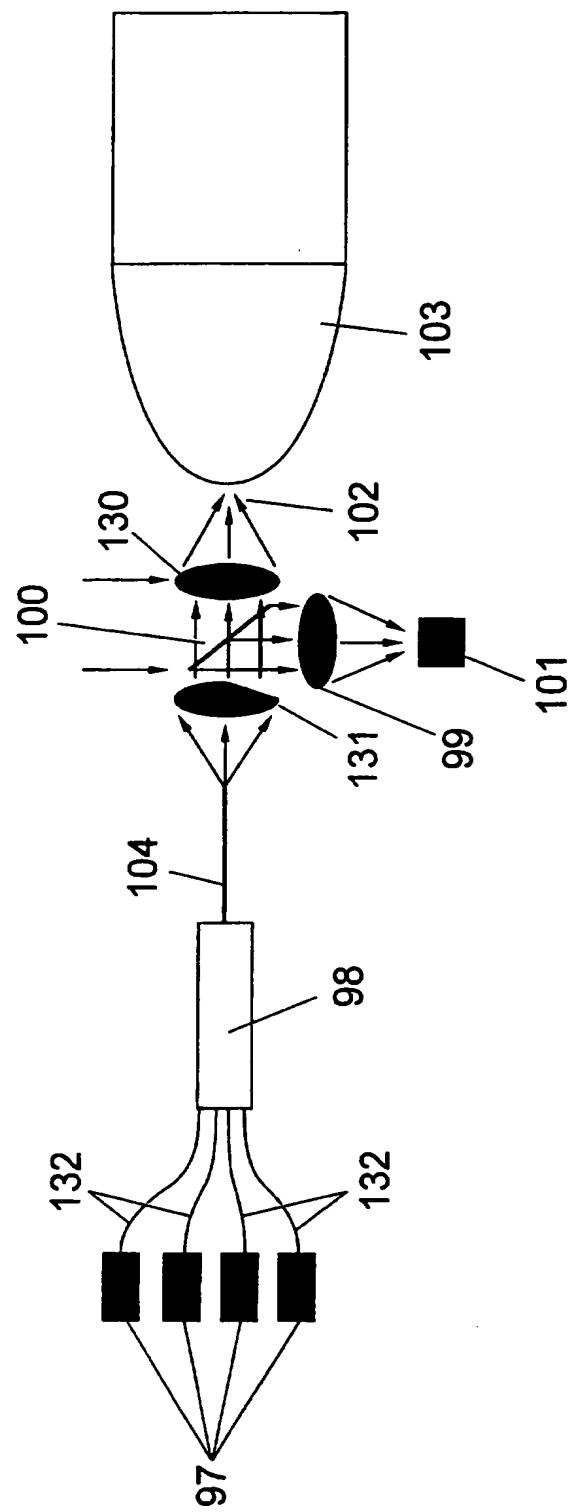


Fig. 12

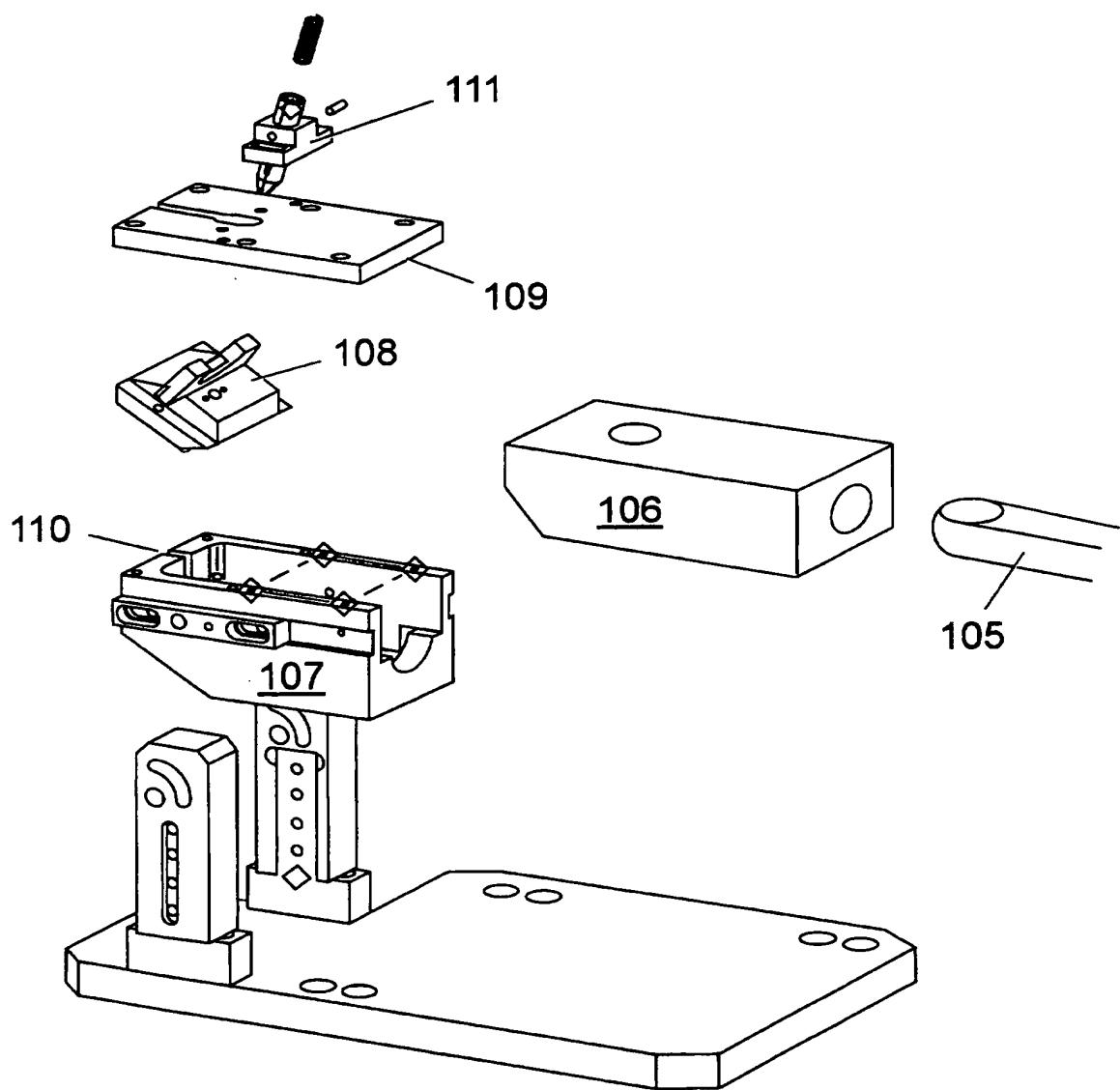
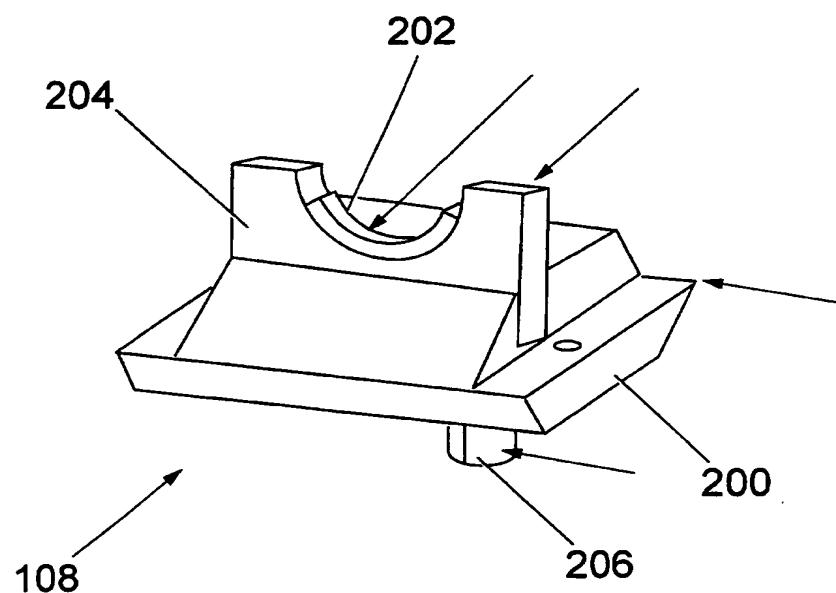


Fig. 13



*Fig. 13a*

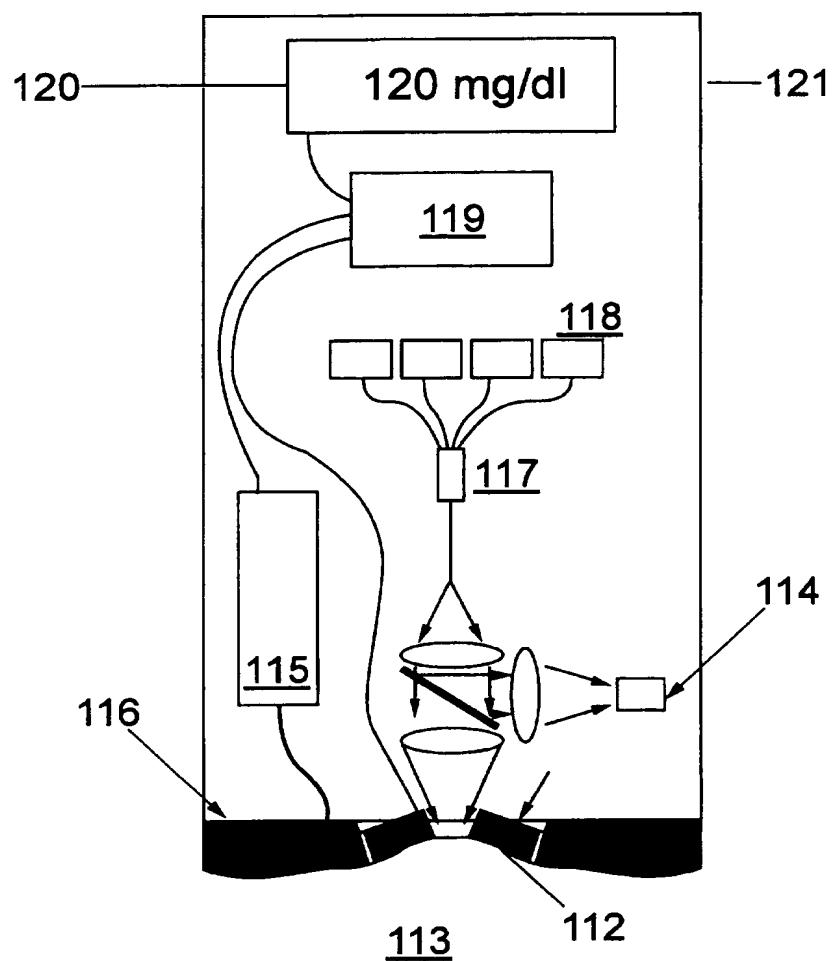


Fig. 14

12 / 16

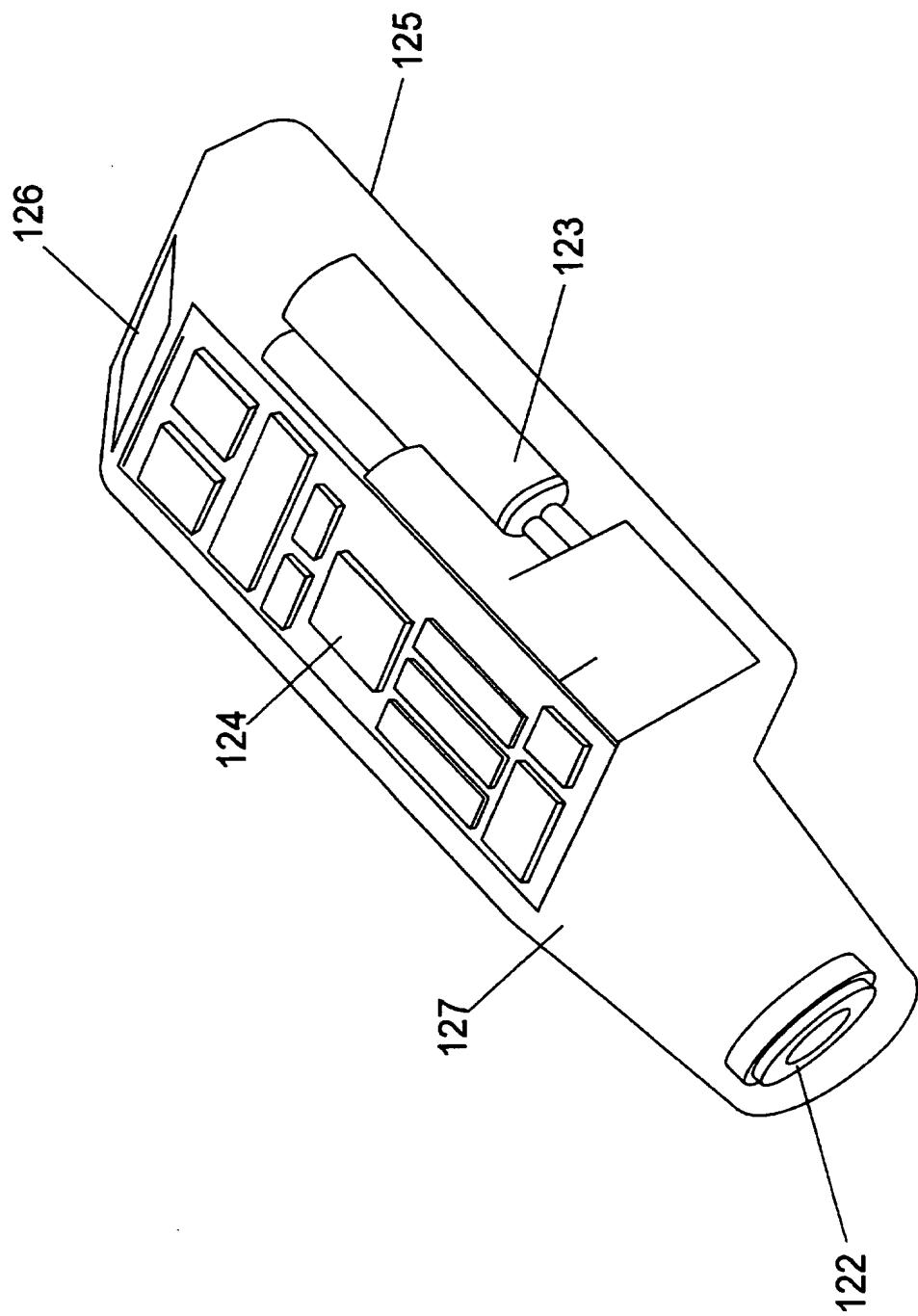


Fig. 15

13 / 16

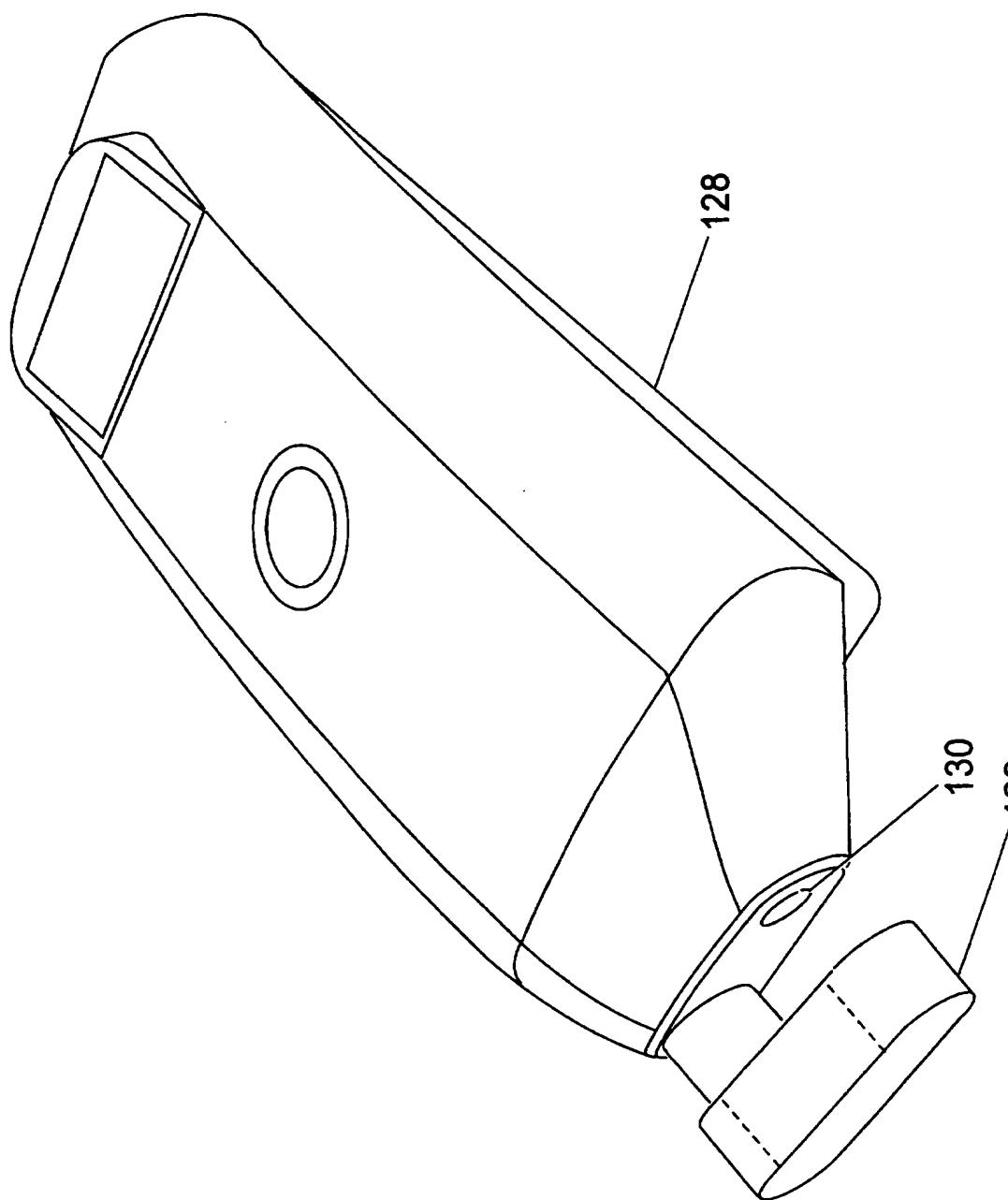


Fig. 16

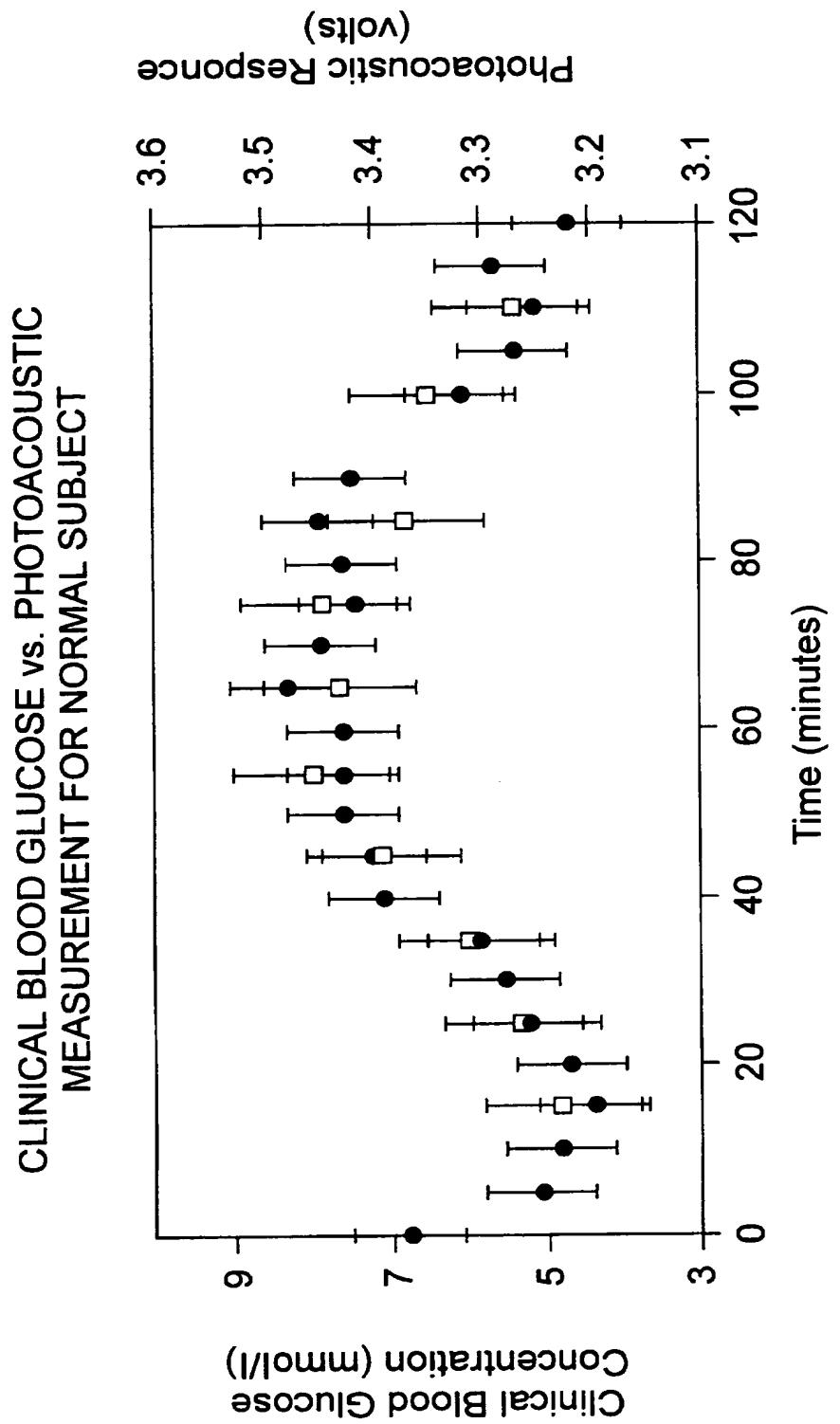


Fig. 17

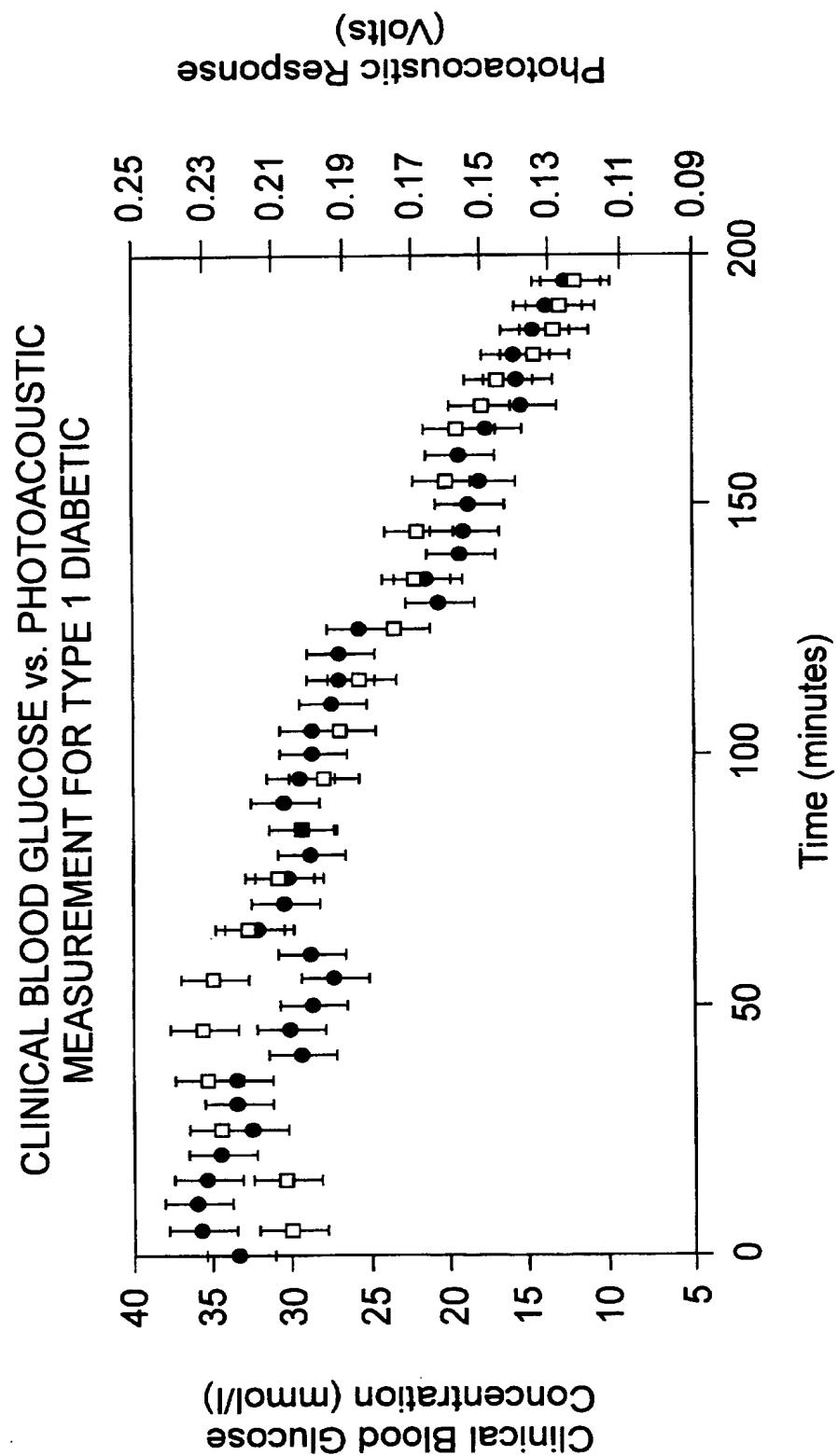


Fig. 18

CLINICAL BLOOD GLUCOSE vs. PHOTOACOUSTIC  
MEASUREMENT FOR TYPE 2 DIABETIC

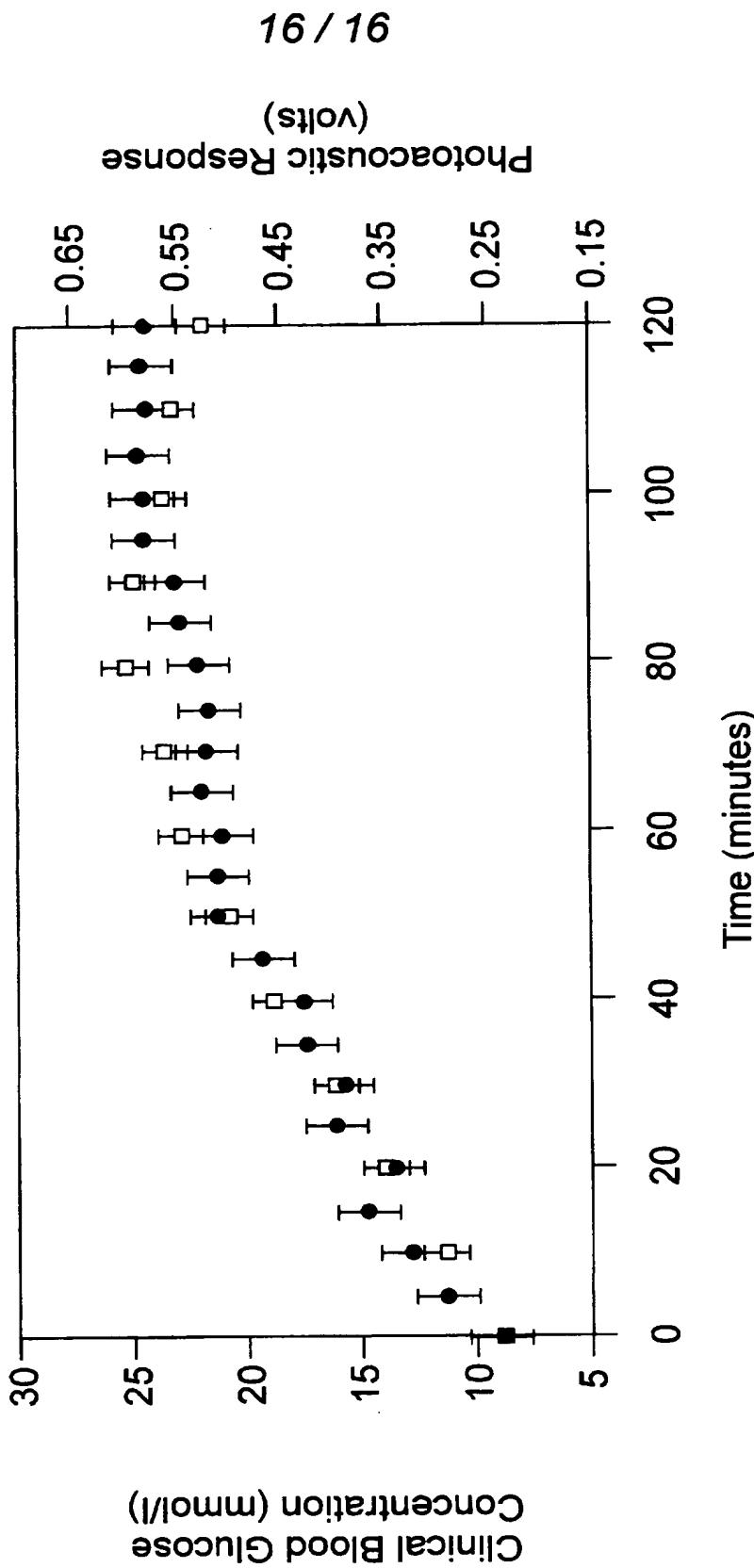


Fig. 19

1        Biological Measurement System

2

3        This invention relates to apparatus for use in non-  
4        invasive in vivo monitoring of physiological substances  
5        such as blood and the like.

6

7        One particular, but not exclusive, application of the  
8        present invention is in the monitoring of blood  
9        glucose, for example in the management of diabetes  
10        mellitus. It is accepted that the management of  
11        diabetes can be much improved by routine monitoring of  
12        blood glucose concentration and clinicians suggest that  
13        monitoring as often as four times per day is desirable.

14

15        The monitoring technique currently available for use by  
16        patients involves using a spring loaded lancet to stab  
17        the finger to obtain a blood sample which is  
18        transferred to a glucose test strip. The concentration  
19        is derived either by reading the test strip with a  
20        reflectance meter or by visual comparison of colour  
21        change against a colour scale. Many diabetics find the  
22        testing onerous as the technique is painful,  
23        inconvenient, messy, potentially embarrassing and  
24        offers a site for the transmittance and acceptance of  
25        infection.

1 Techniques have also been developed for non invasive  
2 measurement using transmittance or reflectance  
3 spectroscopy. However the required instruments are  
4 expensive and it is difficult to obtain accurate and  
5 repeatable measurements.

6  
7 There are also known various types of *in vivo* chemical  
8 sensors. These rely on implanting minimally invasive  
9 sensors under the skin surface, but such sensors have  
10 poor long term reproducibility and bio-compatibility  
11 problems.

12  
13 There is therefore a need for improved means for  
14 routine monitoring of blood glucose in a manner which  
15 is simple and straightforward to use.

16  
17 The present invention makes use of photoacoustic  
18 techniques. The fundamentals of photoacoustic  
19 techniques are well known *per se*. A pulse of light,  
20 typically laser light, is applied to a substance  
21 containing an analyte of interest in solution or  
22 dispersion, the wavelength of the applied light being  
23 chosen to interact with the analyte. Absorption of the  
24 light energy by the analyte gives rise to microscopic  
25 localised heating which generates an acoustic wave  
26 which can be detected by an acoustic sensor. These  
27 techniques have been used to measure physiological  
28 parameters *in vitro*.

29  
30 US Patents 5348002 and 5348003 (Caro) propose the use  
31 of photoacoustics in combination with photoabsorption  
32 for the measurement of blood components *in vivo*.  
33 However, the arrangement proposed by Caro has not been  
34 demonstrated as a workable system and may suffer from  
35 interference to a degree which would preclude useful  
36 acoustic signals, and since they would also suffer from

1 interference and resonance effects from hard structures  
2 such as bone.

3

4 It has also been proposed by Poulet and Chambron in  
5 Medical and Biological Engineering and Computing,  
6 November 1985, Page 585 to use a photoacoustic  
7 spectrometer in a cell arrangement to measure  
8 characteristics of cutaneous tissue, but the apparatus  
9 described would not be suitable for measuring blood  
10 analytes.

11

12 Published European Patent Application 0282234A1  
13 (Dowling) proposes the use of photoacoustic  
14 spectroscopy for the measurement of blood analytes such  
15 as blood glucose. This disclosure however does not  
16 show or suggest any means which would permit the  
17 required degree of coupling to body tissues for use in  
18 vivo.

19

20 Accordingly, the present invention provides a sensor  
21 head for use in photoacoustic in vivo measurement,  
22 comprising a housing shaped to engage a selected body  
23 part, light transmission means terminating in said  
24 housing so as to transmit light energy from a light  
25 source to enter the body part along a beam axis, and  
26 acoustic transducer means mounted in the housing to  
27 receive acoustic waves generated by photoacoustic  
28 interaction within the body part, the acoustic  
29 transducer means being disposed in the housing to  
30 receive said acoustic wave in a direction of high  
31 acoustic energy.

32

33 The expression "direction of high acoustic energy" is  
34 used herein to denote a direction other than the  
35 forward direction of the light beam. Preferably, the  
36 transducer means is disposed so as to intercept

1 acoustic energy propagating at right angles to the  
2 optical beam axis, or at an angle to the optical beam  
3 axis which may be down to about  $20^\circ$ , typically about  
4  $45^\circ$ .

5

6 An exact measure of the angle of high acoustic energy  
7 can be worked out but is dependent upon the specific  
8 geometry of the light source, the properties of the  
9 tissue and the absorption coefficient of the tissue.

10 One model for understanding the propagation of the  
11 acoustic energy in any homogenous media was developed  
12 by Huyghens and is called the principle of  
13 superposition. In this model each volume element that  
14 is illuminated by the light generates an acoustic  
15 pressure wave that radiates outward in a spherical  
16 manor. The magnitude of the pressure wave at each  
17 volume element depends on the intensity of the optical  
18 beam at that location, the absorption coefficient of  
19 the material at that location, the wavelength of light  
20 and on several other physical properties of the  
21 material such as the speed of sound and the specific  
22 heat. The signal measured at the detector is just the  
23 superposition of all pressure waves from all points  
24 that are illuminated by the source light. An  
25 analytical solution for the pressure wave has been  
26 worked out for a few cases in aqueous material. The  
27 analytical case that best matches the in-vivo  
28 measurements is that of a cylindrical optical beam  
29 propagating in a weakly absorbing material. In this  
30 case the direction of highest acoustic energy is  
31 perpendicular to the optical axis. The base detector  
32 location is with the plane of the detector  
33 perpendicular to the acoustic energy, or parallel to  
34 the optical axis. This is because the acoustic  
35 detector has the highest sensitivity when the acoustic  
36 energy strikes the detector perpendicular to the plane

1 of the detector. This analytical model is not  
2 completely accurate for the in-vivo measurement case  
3 because of scattering of the tissue and because the  
4 tissue absorbs more than the model predicts. These  
5 differences indicate that a different position for the  
6 detector will be optimal. A detailed numeric model is  
7 required to determine the best detector location and is  
8 dependent upon the beam properties (focused to a point,  
9 colligated, etc.), body site (finger, earlobe, arm  
10 etc.) and wavelength. One skilled in the art can  
11 readily develop an appropriate mode. However, suitable  
12 locations for a detector will generally be at an angle  
13 to the optical axis. Angles between 40 and 90 degrees  
14 should be suitable.

15

16 In one preferred arrangement, the acoustic transducer  
17 means is arranged parallel to the optical beam axis.  
18 This arrangement is particularly suitable for use where  
19 the selected body part is the distal portion of a  
20 finger, in which case the housing may include a  
21 generally half-cylindrical depression in which the  
22 finger may be placed with the light transmission means  
23 aimed at the end of the finger.

24

25 Preferably, the acoustic transducer means comprises a  
26 piezoelectric transducer which most preferably is of a  
27 semi-cylindrical shape. This transducer may be  
28 provided with a backing of lead or other dense  
29 material, and the backing may have a rear surface  
30 shaped to minimise internal acoustic reflection.

31

32 Alternative transducer means include a capacitor-type  
33 detector, which is preferably small and disk-shaped; an  
34 integrated semiconductor pressure sensor; and an  
35 optical pressure sensor, for example based on an  
36 optical fibre.

1       In an alternative arrangement, the plane of the  
2       transducer may be arranged to be perpendicular to the  
3       optical axis to detect the acoustic wave which is  
4       propagating in a direction opposite to the direction of  
5       the light beam. For example, the acoustic transducer  
6       means may be part-spherical with an aperture to allow  
7       access for the light beam. This may be particularly  
8       suitable for engagement with a body part other than the  
9       finger, for example the back of the arm.

10  
11      The generation of a surface acoustic wave is an  
12      inherent aspect of the in vivo pulsed photoacoustic  
13      generation in tissue and may be used to characterize  
14      tissue properties such as density. A surface wave  
15      detector may be provided in the sensing head assembly.  
16

17      Preferably means are provided for ensuring a consistent  
18      contact pressure between the selected body part and the  
19      acoustic transducer means. In the case where the  
20      selected part is the distal portion of the finger, said  
21      means may be provided by mounting the portion of the  
22      housing engaged by the finger in a resiliently biased  
23      fashion against the remainder of the housing, and  
24      providing means to ensure that measurement is effected  
25      when the predetermined force or pressure is applied by  
26      the subject against the resilient bias. In the case  
27      where the selected part is the earlobe, said means may  
28      be provided by placing the ear between two plates and  
29      applying pressure to the ear with springs or weights or  
30      other force method. The two plates holding the ear may  
31      contain a removable insert. The two plates may be flat  
32      or may be of another shape to optimally position the  
33      detector with respect to the beam axis.  
34

35      In addition, the present invention provides a sensor  
36      head for use in photoacoustic in-vivo measurements,

1 comprising a housing shaped to receive a removable  
2 insert, a removable insert that engages a selected body  
3 part, the insert being fitted to an individual,  
4 allowing for a range of sizes of body parts to be used,  
5 and further comprising light transmission means  
6 terminating in or near said removable insert so as to  
7 transmit light energy from a light source or sources to  
8 enter the body part along a beam axis, and an acoustic  
9 transducer means mounted in the housing or in the  
10 removable insert to receive acoustic waves generated by  
11 photoacoustic interaction within the body part to  
12 receive said acoustic waves in a direction of high  
13 acoustic energy.

14  
15 From another aspect the present invention provides an  
16 in vivo measuring system comprising a sensor head as  
17 hereinbefore defined in combination with a light source  
18 coupled with the light transmission means, and signal  
19 processing means connected to receive the output of the  
20 acoustic transducer means and to derive therefrom a  
21 measurement of a selected physiological parameter.

22  
23 Preferably, the light transmission means is a fiber  
24 distribution system where each light source is  
25 connected to an individual fiber and when multiple  
26 light sources are used the multiple fibres are joined  
27 by some standard fiber combining method, such as a  
28 wavelength division multiplexer or a fiber coupler.  
29 The fiber that comes from the light source, or contains  
30 the combined light for a multiple source system, is  
31 then terminated in proximity to the body part being  
32 measured. The fiber could be in contact with the body  
33 part or alternatively standard optics, such as lenses,  
34 beamsplitters and such, could be employed to convey the  
35 light from the end of the fiber to the body part. A  
36 reference detector or several reference detectors and

1      beam splitters can be added to the optical distribution  
2      system to determine the energy of the light entering  
3      the body part.

4  
5      Alternatively, the optical distribution system may  
6      contain mechanical holders, lenses and such to convey  
7      the light from the source, or sources, to a location in  
8      proximity to the body part being measured. A reference  
9      detector or several reference detectors and  
10     beam splitters can be added to the optical distribution  
11     system to determine the energy of the light entering  
12     the body part.

13  
14     The acoustic signal from the detector contains  
15     information in both time and frequency, and there may  
16     be information from several sources. The processing  
17     means is preferably a multi-dimensional processing  
18     method, such as Classical Least Squares (CLS) or  
19     Partial Least Squares (PLS). Alternatively the  
20     processing method may be more flexible, such as a  
21     Neural Network. In addition to these methods the  
22     signals may be analysed for their frequency content  
23     using such techniques as Fourier Analysis or Frequency  
24     Filtering. In addition techniques may be employed that  
25     use time information such as the time delay from source  
26     trigger. Techniques that combine both frequency and  
27     time information may be employed, such as Wavelet  
28     analysis.

29  
30     The light source is preferably a laser light source and  
31     is most suitably a pulsed diode laser, but may utilise  
32     a set of such lasers or utilise a tunable laser source.  
33     In a particularly preferred form, suitable for use in  
34     measuring blood glucose concentration, a laser diode is  
35     used with a wave length in the range of approximately  
36     600 nm to 10,000 nm and a pulse duration of the order

1 of 5 to 500 ns.

2  
3 The delivery to the measurement site may be either  
4 directly or by optical fibre with a suitable optical  
5 element to focus the beam into the tissue.

6  
7 Preferably means are provided for time multiplexing  
8 multiple sources when multiple sources are used. Each  
9 source is switched on, and it generates an optical  
10 pulse, or a set of optical pulses. This pulse, or set  
11 of pulses, generates an acoustic signal that is  
12 detected by the detector. Each source is pulsed in  
13 sequence until all sources have been used to generate  
14 their own signal.

15  
16 The measuring system may conveniently be in the form of  
17 a self contained system including a power supply and a  
18 readout, which may be carried on the person and used at  
19 any convenient time.

20  
21 It is also possible for such a self contained system to  
22 incorporate, or to be provided with facilities for  
23 connection to, a cellular telephone, two-way pager or  
24 other communication device for routine transmission of  
25 measurements taken to a central data collection point.

26  
27 In addition the measuring system may have provision for  
28 manipulating the body part under measurement and for  
29 performing additional measurement of the tissue to get  
30 other information about the state of the physiology of  
31 the issue. It is well-known in the art that squeezing  
32 a section of tissue to increase the pressure and then  
33 releasing the pressure will cause changes in the total  
34 blood volume in the measurement site. The present  
35 invention may allow for this type of manipulation  
36 including the squeezing of a body part, such as an

1 earlobe, and making photo acoustic measurements at  
2 several different pressures. The present invention may  
3 also allow for the measurement of the temperature of  
4 the body site and to apply a correction to the  
5 measurements based upon the temperature of the body  
6 site.

7 Another type of physiological manipulation is body  
8 temperature. It is known in the art that several  
9 parameters involved in the detection of the photo  
10 acoustic signal, such as the speed of sound, are  
11 dependent upon the temperature of the medium the signal  
12 is propagating through (the tissue). Also the  
13 profusion of the blood in the small capillaries is  
14 dependent upon the temperature of the tissue.  
15 Additional information about the tissue can be obtained  
16 if the photo acoustic measurement is made at several  
17 temperatures, both higher and lower than ambient  
18 temperature. This additional information is used to  
19 better eliminate interferences to the determination of  
20 the analyte under investigation. These are only two  
21 examples of manipulating the body site and are not  
22 intended to be an exhaustive list, and they can be used  
23 in combination with other manipulation techniques.  
24

25 The in-vivo measuring system may comprise a means for  
26 storing calibration coefficients or operation  
27 parameters or both calibration coefficients and  
28 operational parameters, in order to calibrate the  
29 instrument and to set critical operational parameters.  
30

31 Another aspect of the present invention provides a  
32 means for adjusting the calibration coefficients and  
33 operational parameters to be specific to a particular  
34 person and may be used to adjust for such things as  
35 body part size, skin color, skin condition, amount of  
36

1 body fat, efficiency of the detector and efficiency of  
2 the source(s).

3

4 In addition the present invention may provide for  
5 having the specific calibration coefficients and  
6 operational parameters be contained in a storage site  
7 located in the removable insert. This allows for the  
8 system to be both mechanically and operationally  
9 configured to a particular individual. Additionally  
10 the invention may allow for the calibration  
11 coefficients and operational parameters to be stored in  
12 two locations, one in the non-removable housing and one  
13 in the removable insert with some of the coefficients  
14 and parameters stored in each location. This allows  
15 for reader system coefficients to be stored in the  
16 reader and coefficients specific to an individual to be  
17 stored in the removable insert for that person,  
18 enabling many people to use the same reader.

19

20 Another aspect of the present invention provides means  
21 for connecting the non-invasive measuring system to an  
22 invasive measuring system for the purpose of  
23 calibrating or adjusting the operational parameters of  
24 the non-invasive measuring system. Such connection may  
25 be accomplished, but is not limited to, communication  
26 by a wire, IR link or radio waves.

27

28 Another aspect of the present invention provides a  
29 method for removing instrument drift from the  
30 measurement comprising the steps of:

31

- 32 1. Placing a standard in the reader in place of the  
33 body part.
- 34
- 35 2. Measuring the signal from the standard for each  
36 wavelength and storing the values in the

1                   calibration storage location.

2

3       3. Before making a measurement of a body part,  
4                   placing the calibration standard in the reader.

5

6       4. Measuring the signal from the standard for each  
7                   source.

8

9       5. Comparing the just measured standard values to the  
10                  stored calibration values.

11

12       6. Calculating correction factors for each source  
13                  wavelength.

14

15       7. Removing the standard and placing the body part in  
16                  the reader.

17

18       8. Measuring the signal from the body part for each  
19                  source.

20

21       9. Adjusting the measured values using the calculated  
22                  correction factors.

23

24       In addition to the signal correction factors a  
25                  correction factor can be calculated for the instrument  
26                  temperature. This can be applied to each signal with a  
27                  different correction coefficient.

28

29       The invention further provides a method of measuring a  
30                  biological parameter in a subject, the method  
31                  comprising the steps of:

32

33                  directing one or more pulses of optical energy  
34                  from the exterior into the tissue of a subject  
35                  along a beam axis, the optical energy having a  
36                  wavelength selected to be absorbed by tissue

1 components of interest, thereby to produce a  
2 photoacoustic interaction;  
3  
4 detecting acoustic energy resulting from said  
5 photoacoustic reaction by means of a transducer  
6 positioned to intercept acoustic energy  
7 propagating in a direction other than the forward  
8 direction of said beam axis; and  
9  
10 deriving from said detected acoustic energy a  
11 measure of the parameter of interest; and a  
12 corresponding apparatus.  
13  
14  
15 Embodiments of the invention will now be described, by  
16 way of example only, with reference to the accompanying  
17 drawings in which:-  
18  
19 Figs. 1A, 1B and 1C are side views illustrating the  
20 principle of operation of one embodiment of the  
21 present invention;  
22  
23 Fig. 2 is a schematic perspective view showing a  
24 sensor head for use in carrying out the  
25 measurement illustrated in Fig. 1;  
26  
27 Fig. 3. is a cross section view of the sensor head  
28 of Fig. 2;  
29  
30 Fig. 4 is a side view of the sensor head of Fig.  
31 2;  
32  
33 Fig. 5 is a schematic perspective view of an  
34 apparatus incorporating the sensor head of Figs. 2  
35 to 4;  
36

1       Fig. 6 is a perspective view illustrating an  
2       alternative form of sensor head;

3  
4       Fig. 7 is a schematic end view showing another  
5       form of sensor head;

6  
7       Figs. 8a and 8b are a cross-sectional side view  
8       and a plan view, respectively, of a further sensor  
9       head;

10  
11      Fig. 9 is a cross-sectional side view of one more  
12      embodiment of sensor head;

13  
14      Fig. 10 is a perspective view of one type of ear  
15      interface apparatus;

16  
17      Fig. 11 is a schematic of a multiple laser optical  
18      distribution system using lenses, mechanical  
19      mounts and a reference detector;

20  
21      Fig. 12 is a schematic of a multiple laser optical  
22      distribution system using fiber optic cables and a  
23      fiber Wavelength Division Multiplexer (WDM), a  
24      beam splitter and a reference detector;

25  
26      Fig. 13 is a perspective view of a finger  
27      interface apparatus with removable inserts that  
28      are moulded to fit one individual;

29  
30      Fig. 13A shows part of the apparatus of Fig. 13 in  
31      greater detail;

32  
33      Fig. 14 is a schematic of a semi-spherical  
34      detector that contains a hole for the light beam,  
35      with a vacuum system and a fiber distribution  
36      system;

1

2       Fig. 15 is a perspective view showing one form of  
3       the instrument utilizing the vacuum body  
4       interface, a semi-spherical detector and the  
5       multiple laser source with lenses and mechanical  
6       housing;

7

8       Fig. 16 is a perspective view showing one form of  
9       the instrument using an ear lobe body interface,  
10      with the added feature of being able to manipulate  
11      the pressure on the ear lobe; and

12

13      Figs. 17, 18 and 19 are graphs illustrating an  
14      example.

15

16      Referring to Fig 1, an important feature of the present  
17      invention lies in introducing light energy along an  
18      axis into an area of soft tissue and detecting the  
19      resulting acoustic response transverse to that axis.  
20      Accordingly, in the arrangement of Fig 1A light energy  
21      from a diode laser (not shown) is transmitted via a  
22      fibre-optic guide 10 to the tip of a finger 12. The  
23      photoacoustic interaction occurs in an approximately  
24      cylindrical region indicated at 14 from which acoustic  
25      energy is radiated in a generally cylindrical manner  
26      and is detected by a transversely arranged acoustic  
27      transducer 16.

28

29      In Figs 1B and 1C, the principle is similar. The  
30      finger 12 is pressed against a support with force F.  
31      In Fig 1B, the incident light beam indicated at L is  
32      directed as in Fig 1A, and the transducer 16 is at an  
33      angle of 45 degrees thereto. In Fig 1B, the angle is  
34      90 degrees as in Fig 1A, but the incident beam is  
35      directed differently into the fingertip.

36

1      In the present embodiment, the laser wavelength is  
2      chosen to achieve high degree of absorption by glucose  
3      present in the blood. A suitable wavelength is in the  
4      range approximately 1000 to 3000 nm. The laser pulse  
5      duration is chosen to be short, typically of the order  
6      of 5 to 500 ns, in order to minimise thermal diffusion  
7      and thus to optimise the acoustic waveform. For the  
8      same reasons, it is desirable to use a spot size which  
9      is sufficiently small to minimise thermal diffusion,  
10     typically a spot size of the order of 0.05 mm to  
11     0.50 mm.

12  
13     The efficiency of the photoacoustic detection is also  
14     influenced by the positioning and dimensions of the  
15     acoustic transducer in relation to the characteristic  
16     extinction length of the tissue at the principal  
17     wavelengths chosen for measurement. In the fingertip  
18     arrangement of Fig. 1, the system efficiency will be  
19     improved by optimising the length of the transducer  
20     crystal parallel to the axis of the finger, but the  
21     length should not be so great as to give rise to  
22     undesired signals which would occur at the point of  
23     entry of the optical energy into the finger and by  
24     reason of interaction of the acoustic energy with bone  
25     or other hard tissue.

26  
27     A second limit on the size of the acoustic detector  
28     derives from the wavelength of the acoustic wave in the  
29     tissue. Again making use of Huyghens principle of  
30     superposition we view each point of tissue, that is  
31     illuminated by the incoming light, as a point source  
32     that generates a spherical pressure wave. The signal  
33     measured at the detector is just the superposition of  
34     all pressure waves from all points that are illuminated  
35     by the source light. Normally if the size of the  
36     detector is increased then the signal should also

1 increase because more energy is received by the  
2 detector. However if the acoustic detector is too  
3 large then a pressure wave generated from a tissue  
4 element will create a pressure wave that will strike  
5 the both ends of the detector. If the paths length  
6 from the tissue element to the first end of the  
7 detector is different than the path length to the  
8 second end of the detector and if this difference in  
9 path length is about one half of the acoustic signal  
10 wavelength then the signal will destructively interfere  
11 with itself and will reduce the magnitude of the  
12 measured signal.

13

14 Referring to Fig 2, one manner of carrying out the  
15 arrangement shown in Fig 1 makes use of a sensor head  
16 having a finger rest 18 which is slidably moveable  
17 within housing 20 closed by a front plate 22. The user  
18 inserts his finger in a semi-cylindrical depression 24  
19 in the finger rest 18 with the finger tip engaged  
20 against an end surface 28 which includes an exit face  
21 26 of the optical fibre 10. The finger is then pressed  
22 downwardly against a resilient bias to enable a  
23 standardised contact to be obtained between the skin  
24 and the acoustic transducer. The finger tip may first  
25 be dipped in water or coated with an aqueous gel to  
26 improve the acoustic coupling.

27

28 Referring to Figs 3 and 4, in this preferred  
29 arrangement the acoustic transducer comprises a semi-  
30 cylindrical piezoelectric transducer 30. The  
31 transducer 30 is provided with a backing member 32 of  
32 lead or another dense substance, the rear face 34 of  
33 which is shaped in irregular curves. The use of the  
34 semi-cylindrical transducer 30 maximises the area for  
35 reception of acoustic energy from the finger, while the  
36 use of a dense backing material minimises ringing

1 effects within the transducer. Additionally, the rear  
2 face 34 is shaped as shown to reduce reflection of  
3 acoustic energy back towards the piezo crystal.

4  
5 Fig 3 also shows the finger rest biased upwardly by the  
6 use of constant tension springs 38.

7  
8 Fig 5 illustrates schematically the apparatus of Figs.  
9 2 and 3 embodied in a self-contained, portable blood  
10 monitoring apparatus including a user readout 40. An  
11 apparatus of this nature allows a diabetic to monitor  
12 blood glucose concentration in a convenient manner, as  
13 frequently as may be desired, and in a painless and  
14 discreet manner.

15  
16 Other forms of photoacoustic sensor head are possible  
17 within the scope of the present invention. For  
18 example, Fig. 6 shows an arrangement in which a light  
19 guide 50 and an acoustic transducer 52 are applied to a  
20 finger 54 by means of a hinged clamp member 56. Fig. 7  
21 shows a finger 60 engaged by a light guide 62 and an  
22 acoustic transducer 64 which are carried on a moveable  
23 assembly 66 with the finger 60 being trapped between  
24 the moveable assembly 66 and a fixed anvil 68.

25  
26 It is also possible to arrange the sensor head to co-  
27 operate with a soft tissue surface of the body, for  
28 example a soft part of the abdomen. Figs. 8a and 8b  
29 show an arrangement in which a cup shaped member 70,  
30 suitably of rubber, causes a light guide 72 and an  
31 acoustic transducer 74 to be contacted with a bulge of  
32 soft tissue 76 which may for example be drawn into  
33 contact by means of a partial vacuum within the member  
34 70 caused by suction through a conduit 78, or by other  
35 mechanical or adhesive means.

36

1 A somewhat similar arrangement is shown in Fig. 9 in  
2 which a planar mount 80 carrying a light guide 82 and  
3 acoustic transducer 84 is secured to a soft area of  
4 body by means of surgical adhesive 86.

5  
6 Referring to Fig. 10, one method of performing  
7 measurement on an ear lobe involves placing the ear  
8 lobe between a fixed plate 87 and a movable plate 88.  
9 The acoustic detector 89 is mounted partially  
10 perpendicular that is at an acute angle, to the beam  
11 axis defined as line going from the center of a lens 90  
12 to the center of a window 91. It has been found that  
13 the system works satisfactorily with the detector 89 at  
14 an angle of 45° to the beam axis. The window 91 and  
15 the detector 89 are placed in direct contact with the  
16 ear and the opposite plate 88 places pressure on the  
17 ear using a suitable mechanism (not shown). This  
18 particular embodiment of the ear interface apparatus  
19 incorporates an alignment ring 92 which is temporarily  
20 attached to the ear and fits over the window housing 91  
21 to aid in aligning ear into the same location every  
22 time.

23  
24 Referring to Fig. 11, one method of combining light  
25 sources into the instrument is to use a mechanical  
26 housing 93 with several holes used to align lenses 95  
27 and laser diodes 94. The housing shown uses a  
28 hexagonal array of seven holes. The sources and lenses  
29 are arranged in such a way that they all focus to the  
30 same location 96 which could be on the surface of the  
31 body part. This design does not show the inclusion of  
32 beamsplitters and reference detectors but they can be  
33 added in an alternative arrangement.

34  
35 An alternative method of combining several sources into  
36 one beam is shown in Fig. 12. Several laser diodes 97

1 are shown coupled to individual fiber optic cables 131.  
2 These cables 132 are combined using a fiber Wavelength  
3 Division Multiplexer (WDM) 98. Alternative combination  
4 methods exist including couplers and multi-fiber  
5 bundles. The combined light exits the WDM 98 in a  
6 single fiber 104 and terminates at the focal point of a  
7 lens 131. This end of the fiber is imaged to the end  
8 of the finger 103 to a spot 102 using another lens 130.  
9 Some of the light is split off the main beam using a  
10 beam splitter 100 and focused onto a reference detector  
11 101 using another lens 99. Additional reference  
12 detectors and/or beamsplitters can be added to the  
13 distribution system without changing its function.  
14 Alternatively a reference detector could look directly  
15 at the body part to measure the light reflecting off  
16 the surface, as a measure of the overall light energy  
17 entering the body part.

18  
19 Referring to Fig. 13, another method of using a finger  
20 as the body part and including removable inserts is  
21 shown. A finger 105 is inserted into an insert 106  
22 that is used to customize the finger holder to a  
23 particular finger. The moulded insert 106 is placed  
24 into a housing 107. The finger 105 is placed against a  
25 semi-cylindrical acoustic detector in a module 108 which  
26 is also attached to the housing 107. A cover 109 for  
27 the housing 107 contains a mechanism 111 to apply  
28 constant force to the finger 105. The light beam 110  
29 is introduced into the finger 105 using a suitable  
30 optical distribution system (not shown). Fig. 13A shows  
31 the module 108 in greater detail. A base 200 carries a  
32 part-cylindrical piezo transducer 202 on a support 204.  
33 206 indicates a coaxial connector to communicate the  
34 transducer signal.

35  
36 Fig. 14 shows a schematic of an alternative to the

1 vacuum arrangement shown in Figs. 8 and 9. In this  
2 system a photoacoustic reader 121 is placed against the  
3 skin 113 with a semi-spherical detector 112 in contact  
4 with the skin 113. A vacuum pump 115 and vacuum seal  
5 116 create a negative pressure and pull the skin 113  
6 against the detector 112. Processing electronics 119  
7 energizes light sources 118 and an optical distribution  
8 system 117 routes the light to the body part through a  
9 hole in the top of the semi-spherical detector 112.  
10 The optical distribution system 117 directs a small  
11 portion of the light to a reference detector 114. The  
12 processing electronics 119 measures the signal from the  
13 acoustic detector 112 and the reference detector 114  
14 for each optical source 119 and calculates the glucose  
15 value. The value is displayed on a display 120.

16

17 Fig. 15 shows a similar system 125, only using another  
18 type of optical distribution system 127. Again a  
19 vacuum pump 123 creates a negative pressure which draws  
20 the skin up to an acoustic detector 122. Processing  
21 electronics 124 signals light sources in optical  
22 distribution system 127 to illuminate and a signal is  
23 generated at acoustic detector 122. The processing  
24 electronics 124 calculates the proper value and  
25 displays it on a display 126.

26

27 Fig. 16 shows an alternative arrangement of a photo-  
28 acoustic reader. In this system 128, the vacuum system  
29 is replaced with an ear squeeze mechanism 129 which  
30 applies pressure to the ear. An acoustic detector 130  
31 detects the signals from the ear lobe.

32

33 In the most straightforward forms of the invention, a  
34 single analyte such as glucose in blood can be measured  
35 by using light of selected wavelengths and by measuring  
36 the area or the amplitude of the received acoustic

1 pulse. It is preferable to make each measurement by  
2 using a train of pulses, for example about 100 pulses,  
3 and averaging the results in order to minimise the  
4 effects of noise and pulse effects in the blood flow.

6 The accuracy of the detection system is governed, in  
7 part, by the Signal to Noise Ratio (SNR) of the system.  
8 Variations in the intensity and duration of the light  
9 source can cause the acoustic signal to contain  
10 variations. A normalization technique, such as taking  
11 the ratio of the acoustic signal to the optical signal,  
12 can significantly reduce the effect of the source  
13 variations, thereby improving the signal to noise ratio  
14 of the system. The optical signal can be measured with  
15 a reference detector, or several reference detectors,  
16 one for each source or one for a wavelength range. An  
17 equation describing this type of normalization follows:

23 In some cases the relationship between the optical  
24 signal and the acoustic signal changes with wavelength  
25 and light intensity. When this is the case the  
26 accuracy of the measurement can be further enhanced by  
27 determining the energy dependence of the photoacoustic  
28 signal. This may be determined by establishing the  
29 specific relationship between the photoacoustic signal  
30 and the incident energy from a set of measurements and  
31 using this relationship to compensate for the non  
32 linear response. An equation describing this type of  
33 normalization is as follows:

35 Acoustic Signal  
36 Normalized Signal =

1 Scaling Factor \*Optical Signal +  
2 Offset

4 Other normalization methods can also apply. The time  
5 interval between the optical pulse and the detection of  
6 the acoustic signal may be used to characterise  
7 physical properties such as the velocity of sound in  
8 the tissue. In addition, in another embodiment of the  
9 device the damping of the acoustic oscillations may be  
10 used to monitor the elastic properties of the tissue  
11 and, in particular, the compressibility. Both of these  
12 aspects may be used in the person to person calibration  
13 of the photoacoustic response.

14

15 More complex analysis of the received acoustic energy  
16 is possible. For example, a time-gating technique may  
17 be used to derive measurement at varying depths within  
18 the tissue being examined. Alternatively, an array of  
19 detectors can be employed to determine the profile of  
20 the absorption of the acoustic signal at different  
21 depths and locations. This depth profile will change  
22 with the absorption coefficient and could be used as  
23 additional information to determine the analyte  
24 concentration. It is also possible to derive  
25 information relating to a number of analytes of  
26 interest by more sophisticated analysis of the received  
27 acoustic energy wave forms, for example by analysis of  
28 the frequency spectrum by Fourier transform or wavelet  
29 analysis techniques.

30

31 Alternatively, or in combination with the frequency  
32 techniques and multiple detectors, multiple light  
33 sources can aid in the determination of the  
34 concentration of a number of analytes.

35

36 There are a number of tissue features which may vary

1 from person to person or with in the same person over  
2 time which impact the photoacoustic signal observed.  
3 To obtain an accurate measurement of a given analyte,  
4 such as glucose, it may be helpful to also determine  
5 the concentration of other analytes such as haemoglobin  
6 which may act as interferants. One approach is to  
7 generate several distinct photoacoustic signals using  
8 excitation light of several different wavelengths. For  
9 example, excitation light of a wavelength of which  
10 haemoglobin absorbs strongly but glucose has little if  
11 any absorption could be used to obtain a measure of the  
12 haemoglobin concentration with which to normalize the  
13 effect of haemoglobin on measurements made on different  
14 persons or on the same person at different times.  
15 These measurements which are to be normalized might be  
16 based on the photoacoustic signal generated by light of  
17 a wavelength at which glucose absorbs.

18  
19 It is also possible to measure the concentration of  
20 such interferants by other means, such as infrared  
21 light absorption, and thus normalize or correct the  
22 photoacoustic signal representative of the desired  
23 analyte for variations in these interferants. Thus,  
24 for example, the photoacoustic signal representative of  
25 glucose could be corrected for variations in  
26 haemoglobin concentration determined by optical  
27 absorption techniques such as those taught in US Patent  
28 No 5,702,284.

29  
30 For the reliable and reproducible determination of  
31 glucose a signal to noise ratio of at least 10,000 is  
32 recommended. In this regard water is typically present  
33 in human tissue of a concentration of about 50 molar  
34 while glucose is present at a concentration of about 5  
35 millimolar in a normal individual.

36

1 Apparatus and method embodying the present invention  
2 have been found to yield accurate and repeatable  
3 results. In the case of blood glucose measurement, the  
4 clinical range of glucose concentration is  
5 approximately 5-10 m mol/l in healthy subjects, and up  
6 to 40 m mol/l in diabetics. An analysis based on  
7 simple absorption models suggests that the change in  
8 photoacoustic signal over this range might be as little  
9 as 0.2%. The present invention has been found to  
10 provide a change in photoacoustic signal of up to 140%  
11 for a change in glucose concentration of 15m mol/l.  
12

13 The precise mechanisms involved are not at present  
14 fully understood. It is believed, however, that  
15 absorption occurs primarily in body plasma and is  
16 modified by the presence of glucose, and that this  
17 affects beam geometry.  
18

19 Example  
20

21 The blood glucose levels of three individuals, one  
22 normal individual, one type 1 diabetic and one type 2  
23 diabetic, were followed over a two hour period  
24 following each individual taking about 75 grams of  
25 glucose orally in an aqueous solution by both  
26 photoacoustics and direct blood measurement. The  
27 results are reported in Figures 17, 18 and 19.  
28 Photoacoustic measurements were made every five minutes  
29 and blood measurements were made every ten minutes. The  
30 blood samples were venous blood samples analysed by the  
31 standard glucose oxidase method using a Yellow Springs  
32 instrument. The error bands for the blood measurements  
33 were derived from the literature accompanying the  
34 testing instrument while those for the photoacoustic  
35 results were based on the averages taken over 1000  
36 pulses. The results were obtained from a configuration

1 similar to that illustrated in Figure 1 in which 10 was  
 2 an end of a 1 km multimode fibre optic cable which was  
 3 placed against the finger 12. The other end received  
 4 600 nanosecond pulses of 1040 nanometer light from a Q  
 5 switched Nd:YAG laser delivering 2.7 micro joules per  
 6 pulse for each measurement. Raman interactions in the  
 7 fibre caused the production of light at additional  
 8 wavelengths as set forth in the following table:

9

10

11

12

13 Wavelength in nm	14 Average pulse energy in microJoules	15 Pulse width in ns	16 Approximate bandwidth in nm
17 1064	18 2.7	19 600	20 4
21 1120	22 2.25	23 500	24 6
25 1176	26 2.0	27 450	28 8
29 1240	30 1.5	31 425	32 12
33 1308	34 0.85	35 400	36 15
37 1390	38 0.3	39 350	40 20
41 1450	42 0.1	43 350	44 20
45 1500	46 0.2	47 350	48 20
49 1550	50 0.18	51 360	52 20

29

30

31

32

33 The resulting photoacoustic signal was detected by a  
 34 5mm disc transducer with a lead backing and fed to an  
 35 amplifier and an oscilloscope. The transducer was  
 36 generally placed as 16 in Figure 1 but was not

1 precisely parallel to the beam axis; its detection  
2 plane was at an angle of about 20 degrees to the beam  
3 axis. The photoacoustic signal was evaluated in terms  
4 of the difference in voltage signal from the positive  
5 peak of the compression to the negative peak of the  
6 relaxation of the acoustic pulse.

7  
8 The change in photoacoustic response correlated well  
9 with the change in blood glucose concentration over the  
10 two hour measurement period. A correlation of 0.89 was  
11 achieved on samples ranging from 4 to 35 m mol/l.

12  
13 Other modifications and improvements may be made to the  
14 foregoing embodiments within the scope of the present  
15 invention as defined in the claims.

16

1       **CLAIMS**

2

3       1. A sensor head for use in photoacoustic in vivo  
4       measurement, comprising a housing shaped to engage  
5       a selected body part, light transmission means  
6       terminating in said housing so as to transmit  
7       light energy from a light source to enter the body  
8       part along a beam axis, and acoustic transducer  
9       means mounted in the housing to receive acoustic  
10      waves generated by photoacoustic interaction  
11      within the body part, the acoustic transducer  
12      means being disposed in the housing to receive  
13      said acoustic wave in a direction of high acoustic  
14      energy.

15

16      2. A sensor head according to claim 1, in which the  
17      acoustic transducer means is arranged at least  
18      partially perpendicular to the optical beam axis.

19

20

21      3. A sensor head according to claim 2, for use where  
22      the selected body part is the distal portion of a  
23      finger, in which the housing includes a generally  
24      half-cylindrical depression in which the finger  
25      may be placed with the light transmission means  
26      aimed at the end of the finger.

27

28      4. A sensor head according to any preceding claim, in  
29      which the acoustic transducer means comprises a  
30      piezoelectric transducer which is of a semi-  
31      cylindrical shape.

32

33      5. A sensor head according to any preceding claim, in  
34      which the acoustic transducer means comprises a  
35      piezoelectric transducer which is provided with a  
36      backing of lead or other dense material.

- 1       6. A sensor head according to claim 5, in which said  
2       backing has a rear surface shaped to minimise  
3       internal acoustic reflection.
- 4
- 5       7. A sensor head according to any of claims 1 to 4,  
6       in which the transducer means comprises a  
7       capacitor-type detector.
- 8
- 9       8. A sensor head according to any of claims 1 to 4,  
10      in which the transducer means comprises a  
11      piezoelectric transducer arranged generally  
12      perpendicular to the optical axis to detect the  
13      acoustic wave which is propagating in a direction  
14      opposite to the direction of propagation of the  
15      light beam.
- 16
- 17      9. A sensor head according to claim 8, in which the  
18      transducer is part-spherical with an aperture to  
19      allow access for the light beam.
- 20
- 21      10. A sensor head according to any preceding claim,  
22       including a surface wave detector for  
23       characterizing tissue properties.
- 24
- 25      11. A sensor head according to any preceding claim,  
26       including means for ensuring a consistent contact  
27       pressure between a selected body part and the  
28       acoustic transducer means.
- 29
- 30      12. A sensor head according to claim 11, for use where  
31       the selected part is the distal portion of a  
32       finger, said means being provided by mounting a  
33       portion of the housing engaged by the finger in a  
34       resiliently biased fashion against the remainder  
35       of the housing, and providing means to ensure that  
36       measurement is effected when a predetermined force

1                   or pressure is applied by the subject against the  
2                   resilient bias.

3

4       13. A sensor head according to claim 11, for use where  
5                   the selected part is the earlobe, said means being  
6                   provided by two plates, between which the earlobe  
7                   may be placed, and means for pressing the plates  
8                   together to apply pressure to the ear.

9

10     14. A sensor head for use in photoacoustic in-vivo  
11                   measurements, comprising a housing shaped to  
12                   receive a removable insert; a removable insert  
13                   that engages a selected body part, the insert  
14                   being fitted to an individual, allowing for a  
15                   range of sizes of body parts to be used; light  
16                   transmission means terminating in or near said  
17                   removable insert so as to transmit light energy  
18                   from a light source to enter the body part along a  
19                   beam axis; and an acoustic transducer means  
20                   mounted in the housing or in the removable insert  
21                   to receive acoustic waves generated by  
22                   photoacoustic interaction within the body part,  
23                   the acoustic transducer means being disposed in  
24                   the housing or insert to receive said acoustic  
25                   waves in a direction of high acoustic energy.

26

27     15. An in vivo measuring system comprising in  
28                   combination: a sensor head as claimed in any  
29                   preceding claim; a light source coupled with the  
30                   light transmission means; and signal processing  
31                   means connected to receive the output of the  
32                   acoustic transducer means and to derive therefrom  
33                   a measurement of a selected physiological  
34                   parameter.

35

36     16. The system of claim 15, in which the light

1           transmission means is a fiber optic distribution  
2           system.

3

4       17. The system of claim 16, in which there is a  
5           plurality of light sources each connected to an  
6           individual fiber and the respective fibers are  
7           joined by a wavelength division multiplexer or a  
8           fiber coupler.

9

10      18. The system of claim 16 or claim 17, in which the  
11           fiber optic distribution system terminates in  
12           contact with the body part.

13

14      19. The system of claim 16 or claim 17, in which the  
15           fiber optic distribution system communicates with  
16           the body part via optical elements such as lenses  
17           and beamsplitters.

18

19      20. The system of claim 15, in which the light  
20           transmission means comprises optical elements  
21           mounted in mechanical holders and arranged to  
22           convey the light from the light source to a  
23           location in proximity to the body part.

24

25      21. The system of claim 19 or claim 20, in which the  
26           light transmission means includes at least one  
27           beamsplitter arranged in the light path to direct  
28           a portion of the light to a respective reference  
29           detector to measure the energy of the light  
30           entering the body part.

31

32      22. The system of any of claims 15 to 21, in which the  
33           signal processing means is adapted to perform a  
34           multi-dimensional processing method.

35

36      23. The system of claim 22, in which the signal

1 processing means is adapted to perform one of  
2 Classical Least Squares or Partial Least Squares.  
3  
4

5 24. The system of any of claims 15 to 21, in which the  
6 signal processing means comprises a Neural  
7 Network.

8

9

10 25. The system of any of claims 15 to 24, in which the  
11 signal processing means is operable to analyse the  
12 signals for their frequency content using one of  
13 Fourier Analysis and Frequency Filtering.

14

15 26. The system of any of claims 15 to 25, in which the  
16 signal processing means additionally applies  
17 techniques that use time information.

18

19 27. The system of claim 26, in which the time  
20 information processed is the time delay from  
21 source trigger.

22

23 28. The system of any of claims 15 to 25, in which the  
24 signal processing means additionally applies  
25 techniques that combine both frequency and time  
26 information.

27

28 29 The system of claim 28, in which the signal  
29 processing means performs wavelet analysis.

30

31 30. The system of any of claims 15 to 29, in which the  
32 light source is a laser light source.

33

34 31. The system of claim 30, in which said laser light  
35 source is selected from a pulsed diode laser, a  
36 set of pulsed diode lasers, and a tunable laser

1 source.

3 32. The system of claim 31, for use in measuring blood  
4 glucose concentration, in which the light source  
5 is a laser diode with a wavelength in the range of  
6 approximately 600 nm to 10,000 nm and a pulse  
7 duration of the order of 5 to 500 ns.

8

9 33. The system of any of claims 30 to 32, in which the  
10 light transmission means is arranged to produce a  
11 spot size of the order of 0.05 mm to 0.50 mm.

12

13 34. The system of any of claims 15 to 29, in which  
14 there are multiple light sources and means are  
15 provided for time multiplexing the multiple  
16 sources such that: each source is switched on and  
17 generates an optical pulse, or a set of optical  
18 pulses, the pulse, or set of pulses, generates an  
19 acoustic signal that is detected by the detector,  
20 and each source is pulsed in sequence until all  
21 sources have been used to generate their own  
22 signals.

23

24 35. The measuring system of any of claims 15 to 34, in  
25 the form of a self contained system including a  
26 power supply and a readout, which may be carried  
27 on the person and used at any convenient time.

28

29 36. The system of claim 35, including facilities for  
30 connection to a cellular telephone, two-way pager  
31 or other communication device for routine  
32 transmission of measurements taken to a central  
33 data collection point.

34

35 37. The system of any of claims 15 to 36, further  
36 including means for manipulating the body part

1       under measurement and for performing additional  
2       measurement of the tissue to obtain other  
3       information about the state of the physiology of  
4       the issue.

5

6       38. The system of claim 37, in which said manipulating  
7       means includes means for squeezing a body part,  
8       such as an earlobe, and means for making photo  
9       acoustic measurements at several different  
10      pressures.

11

12      39. The system of claim 37 or claim 36, including  
13      temperature measurement means for measuring the  
14      temperature of the body site, and in which the  
15      signal processing means is arranged to apply a  
16      correction to the measurements based upon the  
17      temperature of the body site.

18

19      40. The system of claim 39, further including means  
20      for inducing temperatures above and below ambient  
21      in the body part.

22

23      41. The system of any of claims 15 to 40, comprising a  
24      means for storing one or both of calibration  
25      coefficients and operational parameters in order  
26      to calibrate the instrument and to set critical  
27      operational parameters.

28

29      42. The system of claim 41, in which the signal  
30      processing means is operable to adjust the  
31      calibration coefficients and operational  
32      parameters to be specific to a particular person.

33

34      43. The system of claim 42, when dependent upon claim  
35      14, in which the calibration coefficients and  
36      operational parameters specific to a particular

1           person are contained in a storage site located in  
2           the removable insert.

3

4       44. The system of claim 43, in which additionally  
5           calibration coefficients and operational  
6           parameters specific to the reader system are  
7           stored in the non-removable housing.

8

9       45. The measuring system of any of claims 15 to 44,  
10           further including connection means for connecting  
11           the measuring system to an invasive measuring  
12           system for the purpose of calibrating or adjusting  
13           the operational parameters of the non-invasive  
14           measuring system.

15

16       46. The system of claim 45, in which the connection  
17           means is selected from a cable link, IR link or  
18           radio waves.

19

20       47. A method of operating a measurement system as  
21           claimed in claim 34 to remove instrument drift  
22           from the measurement, the method comprising the  
23           steps of:

24

25           1) placing a calibration standard in the reader  
26           in place of the body part;

27

28           2) measuring the signal from the standard for  
29           each wavelength and storing the values in the  
30           calibration storage location;

31

32           3) before making a measurement of a body part,  
33           placing the calibration standard in the  
34           reader;

35

36           4) measuring the signal from the standard for

1 each source;

2  
3       5) comparing the just measured standard values  
4            to the stored calibration values;

6) calculating correction factors for each  
source wavelength.

9           7) removing the standard and placing the body  
10           part in the reader;

11  
12 8) measuring the signal from the body part for  
13 each source; and

15                   9) adjusting the measured values using the  
16                   calculated correction factors.

18 48. The method of claim 47, in which a further  
19 correction factor is calculated for the instrument  
20 temperature.

22 49 A method of measuring a biological parameter in a  
23 subject, the method comprising the steps of:

32                   detecting acoustic energy resulting from said  
33                   photoacoustic reaction by means of a  
34                   transducer positioned to intercept acoustic  
35                   energy propagating in a direction other than  
36                   the forward direction of said beam axis; and

1 deriving from said detected acoustic energy a  
2 measure of the parameter of interest.

3

4 50 The method of claim 49, in which the parameter of  
5 interest is blood glucose, and the optical energy  
6 has a wavelength in the range of approximately 600  
7 mm to 10,000 mm and a pulse duration of the order  
8 of 5 to 500 ms.

9

10 51 The method of claim 49 or claim 50, in which a  
11 train of pulses is applied and the detected  
12 signals are averaged to derive said measure.

13

14 52 The method of any of claims 49 to 51, in which  
15 said measure is derived from the energy of the  
16 detected signal.

17

18 53 The method of any of claims 49 to 52, in which the  
19 optical energy is directed into a body part which  
20 is substantially composed of soft tissue and free  
21 of bone.

22

23 54 Apparatus for measuring a biological parameter in  
24 a subject, the apparatus comprising:

25

means for directing one or more pulses of optical energy from the exterior into the tissue of a subject along a beam axis, the optical energy having a wavelength selected to be absorbed by tissue components of interest, thereby to produce a photoacoustic interaction;

32

33 transducer means arranged to detect acoustic  
34 energy resulting from said photoacoustic reaction  
35 by intercepting acoustic energy propagating in a  
36 direction other than the forward direction of said

1       beam axis; and

2

3       means for deriving from said detected acoustic  
4       energy a measure of the parameter of interest.

5

6       55      Apparatus according to claim 54, in which said  
7        directing means includes means for receiving a  
8        selected body part such that the optical energy is  
9        directed into a portion of the subject's body  
10      which is substantially free of bone.

11

12      56      A method of correcting measurement of an analyte  
13      based on a photoacoustic signal obtained from a  
14      living being comprising determining the  
15      concentration of other constituents in the being  
16      which have a significant effect on the  
17      photoacoustic signal and tend to vary from  
18      individual to individual or over time, and  
19      adjusting the measurement to remove the effect of  
20      variations in the concentrations of said other  
21      constituents.

22

23      57      The method of claim 56 in which the analyte is  
24      glucose.

25

26      58      The method of claim 57 in which the concentration  
27      of haemoglobin is determined and used to adjust  
28      the measurement.

29

30      59      A method of establishing a photoacoustic signal  
31      obtained from a living being comprising using the  
32      ratio of the acoustic signal obtained to the  
33      optical signal which generated the acoustic signal  
34      to determine the concentration of an analyte  
35      present in said being.

36

1       60   The method of claim 59 in which the analyte is  
2       glucose.

3

4       61   A method of normalizing a photoacoustic signal  
5       obtained from directing an optical beam on the  
6       tissue of a living being comprising determining  
7       the dependence of the photoacoustic signal on the  
8       energy of the optical beam from a series of  
9       measurements at different energies for the type of  
10      tissue involved.

11

12

13



Application No: GB 9804828.3  
Claims searched: 1 to 55

Examiner: Grant Bedford  
Date of search: 22 June 1998

**Patents Act 1977**  
**Search Report under Section 17**

**Databases searched:**

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.P): G1G (GPB)

Int Cl (Ed.6): G01N (21/17 33/483 33/487 33/49), A61B (5/00 5/14)

Other: Online: WPI INSPEC

**Documents considered to be relevant:**

Category	Identity of document and relevant passage		Relevant to claims
X	EP 0282234 A1	(DOWLING) See figure 4 and page 8 lines 1 to 3 in particular.	1 and 14 at least
X,E	EP 0829224 A2	(COLUMBUS) See figure 2 in particular.	1 and 14 at least
X,E	EP 0829225 A2	(COLUMBUS) See figure 1 in particular.	1 and 14 at least
X	Medical & Biological Engineering & Computing, Vol. 31(3), pp. 284-290, May 1993		1 and 14 at least
X	Physics in medicine and biology, Vol. 38(12), pp. 1911-1922, Dec 1993		1 and 14 at least

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.